Normalisation of gait EMGs: a re-examination

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Abstract

The purpose of this study was to compare four different methods of normalising electromyograms (EMGs) recorded during normal gait. Comparisons were made between the amplitude, intra-individual variability and inter-individual variability of EMGs. Surface EMGs were recorded from the biceps femoris, semitendinosus, vastus lateralis and vastus medialis of ten males and two females while they walked on a treadmill at a self-selected speed. EMGs from the same muscles were subsequently recorded during isometric maximal voluntary contractions (MVCs) and concentric, isokinetic MVCs that were performed between 0.52 and 7.85 rad·s⁻¹ on a BIODEX dynamometer. EMGs were also recorded during eccentric, isokinetic MVCs between 0.52 and 2.62 rad·s⁻¹.

Gait EMGs were then normalised at 2% intervals of the gait cycle by expressing them as a percentage of the following reference values: the mean (mean dynamic method) and the peak (peak dynamic method) EMG from the intra-individual ensemble average; the EMG from an isometric MVC (isometric MVC method); and the EMG from an isokinetic MVC that occurred with the same muscle action, length and velocity of musculotendinous unit as the gait EMGs (isokinetic MVC method). The isokinetic MVC method produced significantly greater (P < 0.05) intra-individual variability compared to the other methods when it was measured using the variance ratio. Inter-individual variability of gait EMGs, again measured using the variance ratio, was also greatest when they were normalised using the isokinetic MVC method. The pattern and amplitude of EMGs normalised using the isometric MVC method and the isokinetic MVC method were very similar (root mean square difference and absolute difference both less than 3%). It was concluded that the isokinetic MVC method should not be adopted by gait researchers or clinicians as it does not reduce intra- or inter-individual variability anymore than existing normalisation methods, nor does it provide a more representative measure of muscle activation during gait than the isometric MVC method.

Keywords: Reliability; Inter-individual variability; Isometric MVC; Isokinetic MVC

1. Introduction

The importance of normalising electromyograms (EMGs) has long been recognised by researchers and clinicians who record them during gait analysis (e.g. [27,29,35,38]). Gait EMGs were first normalised [14] using a method that divided each point that constitutes the processed EMG by the peak value recorded from the same EMG. This method, subsequently referred to as the peak dynamic method, still appears to be popular among gait electromyographers (e.g. [19,31]). A second and equally popular method, introduced by Dubo et al. [13], divided each data point included in the gait EMG by the peak EMG from an isometric maximal voluntary contraction (MVC) of the same muscle, which is usually performed in the middle of the range of motion. This method, subsequently referred to as the isometric MVC method, was later adopted by Arsenault et al. (e.g. [4]).

Yang and Winter [41] compared a number of normalisation methods in an attempt to establish which would provide a normal gait EMG template and, therefore, improve the use of electromyography as a diagnostic tool in gait analysis. Based on this rationale, the criterion for selecting the best method was the one that most reduced the inter-individual variability of ensemble averaged EMGs [41]. The peak dynamic method and the mean dynamic method (a similar but previously unpublished
method that divided each data point within the gait EMG by the mean value recorded from the same EMG) were included in the comparison. Yang and Winter [41] noted that these two methods do not have the potential to provide any information on the degree of muscle activation that occurs during gait. The authors chose not to include the isometric MVC method in their comparison as they had previously [40] reported that EMGs from isometric MVCs displayed poor reliability. Instead, they also included a method that used the peak EMG from an isometric sub-maximal (50%) voluntary contraction of the same muscle as the denominator in the normalisation equation subsequently referred to as the sub-MVC method. Yang and Winter [41] discovered that the peak dynamic method and the mean dynamic method both reduced inter-individual variability in comparison to the un-normalised EMGs and those normalised by the sub-MVC method. As a consequence of this study, the mean dynamic method was adopted by Winter’s group (e.g. [39]) and a number of other researchers (e.g. [25,28]). Further evidence that the mean dynamic method reduces inter-individual variability more than other normalisation methods was provided by Shiavi et al. [34,35] who also compared the mean dynamic method with the peak dynamic method. They discovered that the mean dynamic method was slightly better at reducing inter-individual variability, particularly during periods of muscle quiescence, due to a relatively lower standard deviation during these periods. Based on this evidence, Shiavi et al. [34,35] also advocated the use of the mean dynamic method particularly when wishing to distinguish between periods of muscle activity and inactivity during gait. However, more recently, Allison et al. [2] and Knutson et al. [23] both warned against using the mean dynamic method or peak dynamic method, although not specifically in gait analysis, as they may remove the true biological variation within a group.

By virtue of the nature of the denominator in its normalisation equation, the isometric MVC method is the only one that has the potential to reveal how active a muscle is during gait. Despite criticism by Yang and Winter [41], the isometric MVC method continues to be used in gait analysis (e.g. [7,12]). However, despite continued use, only Dubo et al. [13] have questioned the suitability of using the EMG from an isometric MVC to normalise gait EMGs, which are clearly recorded during non-isometric contractions. Only a small number of studies have investigated the suitability of using the isometric MVC method to normalise EMGs from non-isometric tasks. Mirka [24] normalised EMGs recorded from sub-maximal isokinetic contractions of the trunk flexor and extensor muscles. Relatively large differences (15–50%) were reported between the isometric MVC method and a method that normalised the task EMGs using EMGs from isometric MVCs performed at the same trunk angle that occurred during the task. In contrast, Knudson and Johnston [22] later reported average absolute differences of less than 7% between the same two methods when used to normalise lower limb muscle EMGs recorded during standing from a seated position. Furthermore, Kellis and Baltzopoulos [21] were the first authors to use EMGs from isokinetic MVCs that had the same muscle action (i.e. concentric or eccentric), joint angle and joint angular velocity as the task EMG as the denominator in the normalisation equation. They discovered a significantly greater ($P < 0.05$) normalised muscle activation amplitude from this method, subsequently referred to as the isokinetic MVC method, when compared to the isometric MVC method when both were used to normalise EMGs from knee flexors and extensors when acting as antagonists during isokinetic MVCs. However, biceps brachii EMGs recorded during isometric elbow flexions and extensions were not significantly different ($P = 0.315$) when normalised by the isometric MVC method and the isokinetic MVC method [5]. Further comparisons between the isometric MVC method and the isokinetic MVC method are warranted as some researchers have reported that peak EMGs from the knee extensors are greater during concentric MVCs than during either eccentric (e.g. [32,37]) or isometric (e.g. [6]) MVCs. Alternatively, Ghori et al. [17] and Amiridis et al. [3] demonstrated no difference in peak EMG between different muscle actions. Furthermore, a number of researchers (e.g. [3,6,37]) have reported that the amplitude of EMGs from knee extensor muscles increased, rather than remaining constant, as the velocity of the isokinetic dynamometer’s lever arm increased during concentric MVCs.

2. Aims

Based on the above evidence, the general opinion provided by gait related review articles is that the peak dynamic method or, preferably, the mean dynamic method should be used if the aim of the analysis is to reduce inter-individual variability and produce a general gait-EMG template (e.g. [33,38]). Alternatively, the isometric MVC method is recommended when the goal is to ascertain the level of muscle activity that is required to walk (e.g. [9,10,29]). However, these opinions are not universally agreed upon and no previous gait related literature makes reference to the use of the isokinetic MVC method. The first aim of this investigation was, therefore, to compare the amplitude of gait EMGs normalised by the isokinetic MVC method with those normalised by the isometric MVC method. The second aim was to compare both the intra-individual variability and inter-individual variability of the isokinetic MVC method with that of the un-normalised EMGs, and the isometric MVC method, mean dynamic method and peak dynamic method.
3. Methods

3.1. Participants

Ten males ((mean ± SD) age 31.7 ± 5.9 years; height 1.81 ± 0.04 m; mass 80.0 ± 12.2 kg) and two females (age 34.5 ± 2.1 years; height 1.65 ± 0.01 m; mass 61.0 ± 1.4 kg) took part in the investigation after reading and signing an informed consent form. All participants were regularly involved in activities that exercised their quadriceps and hamstrings and had no known gait pathology.

3.2. Experimental design

To enable EMGs recorded from lower limb muscles during gait to be normalised by the isometric MVC method and the isokinetic MVC method, it was necessary to record EMGs from the same lower limb muscles during both isometric and isokinetic MVCs. In addition, to be able to apply the isokinetic MVC method, it was also necessary to ascertain the length and velocity of the same lower limb muscles during both gait and the MVCs. The following sub-sections detail how EMGs and musculotendinous unit, subsequently referred to as muscle, kinematics were obtained from the vastus lateralis, vastus medialis, semitendinosus and long head of the biceps femoris during both gait and MVCs; and how the gait EMGs were normalised.

3.2.1. Gait

Each participant performed three 5 s barefoot walking trials on a treadmill (Biodex Medical Systems, Inc., Shirley, New York) set to their normal speed of walking which had been ascertained during a previous habituation session. A footswitch (Median Electronic Industries Ltd., Dorset, UK) was taped to the underside of each participant’s heel prior to the walking trials. Both the footswitch and the EMG recording system were connected to an interface unit (Median Electronic Industries Ltd., Dorset, UK), which enabled the start of each stride to be recorded together with the EMGs by the acquisition software thereby synchronising the two.

3.2.2. Isometric and isokinetic MVCs

MVCs of the knee extensor and flexor muscle groups were performed using a BIODEX 900-800 dynamometer (Biodex Medical Systems, Inc., Shirley, New York). All MVCs were performed while the participant was seated and stabilised, using shoulder, waist and thigh straps, on the BIODEX chair. The lateral condyle of the femur was carefully aligned with the axis of rotation of the dynamometer and the distal end of the calf was secured to the lever arm of the dynamometer using a padded velcro strap.

Isometric MVCs of the knee extensors were performed at 90° and 45° of knee flexion. Angles of 0° (i.e. full extension) and, again, 45° of knee flexion were used for isometric contractions of the knee flexors. MVCs of both muscle groups were performed by reaching maximal force as rapidly as possible and maintaining it for 3 s.

Isokinetic MVCs of the knee extensors and flexors were performed both concentrically and eccentrically. Concentric MVCs were performed at 0.52 rad·s⁻¹ and at each 0.52 rad·s⁻¹ interval up to 6.28 rad·s⁻¹. MVCs were also performed at the two highest concentric velocities permitted by the BIODEX of 6.98 and 7.85 rad·s⁻¹. Eccentric MVCs were also performed at 0.52 rad·s⁻¹ intervals, but between 0.52 rad·s⁻¹ and the highest velocity allowed by the BIODEX of 2.62 rad·s⁻¹. Thus, concentric and eccentric MVCs were performed at 14 and five angular velocities, respectively. Participants were instructed to pull as hard and as fast as they could throughout the full range of motion during the concentric MVCs and resist the motion of the dynamometer’s lever arm with as much force as they could during the eccentric MVCs. All forms of contraction, in particular eccentric, were practiced up to maximal level during a visit to the laboratory that usually occurred a few days before testing.

MVCs were grouped as isometric, slow concentric (0.52–2.62 rad·s⁻¹), mid-concentric (3.14–5.23 rad·s⁻¹), fast concentric (5.76–7.85 rad·s⁻¹) and eccentric (0.52–2.62 rad·s⁻¹). The order in which individuals performed each group of MVCs was randomised using a latin squares design. Within the isometric group, the order of knee flexion and extension was also randomised. Knee extensors were tested first in the concentric groups, and the knee flexors used first in the eccentric group. The average range of motion for the concentric MVCs was 81 ± 6°. This had to be reduced by approximately 5% at the limits of flexion and extension of eccentric MVCs to allow participants to generate enough force to initiate motion of the lever arm. Following a practice to re-familiarise individuals with the type and velocity of contraction, all MVCs were preceded by three sub-maximal contractions of increasing force. At least 3 min elapsed between each set of three MVCs and at least 5 min between each MVC group to minimise the effects of fatigue. During each MVC, participants were encouraged to observe the development of the torque-time trace on the BIODEX PC monitor.

Both the BIODEX and the EMG recording system were connected to an interface unit (Median Electronic Industries Ltd., Dorset, UK), which enabled the angular position of the lever arm of the BIODEX to be recorded together with the EMGs by the acquisition software thereby synchronising the two.
3.3. Calculation of muscle kinematics

First, a VICON 140 motion analysis system (Oxford Metrics Ltd., Oxford, Oxfordshire, UK) was used to record the 3D trajectories of nine 2.5 cm diameter reflective markers overlaying anatomical landmarks on the pelvis and right lower limb. Markers were placed over the anterior superior iliac spines, midway between the posterior iliac spines and on the thigh, knee, shank, ankle, heel and toe. More precise locations of these markers can be found in Davis et al. [8]. The 3D co-ordinates of the markers, together with the length of the leg and width of the knee and ankle, were subsequently used as an input into VICON Clinical Manager software (Oxford Metrics Ltd., Oxford, Oxfordshire, UK) which created a skeletal model of the pelvis, thigh and shank. The model assumed each segment to be rigid and represented by a set of three orthogonal axes that were embedded into it and originated from the midpoint between the anterior superior iliac spines, the knee joint centre and the ankle joint centre, respectively. The positions of the hip, knee and ankle joint centres in relation to the centre of the reflective markers were based on the algorithm developed by Davis et al. [8]. Rotations of the pelvis, thigh and shank around each of their respective axes during gait and the MVCs were then used as an input into the Software for interactive musculoskeletal modelling (SIMM/Gait) for Windows (Musculographics Inc., Evanston, Illinois) which included a musculoskeletal model of the lower limb. The model was developed by Delp et al. [11] and enabled the lengths of the four muscles to be calculated at 2% intervals of the gait cycle or range of motion of MVCs. The rate of change in length of each muscle (i.e. muscle velocity) was subsequently calculated using finite differences.

3.4. Recording and processing of EMGs

A DelSys Bagnoli-8 EMG System (DelSys Inc., Boston, MA) was used to record EMGs from the four muscles during gait and MVCs. Electromyographic signals were detected from each muscle by two electrodes set into a differential pre-amplifier (gain × 10, input impedance > 1000 TΩ, common mode rejection ratio > 80 dB, noise = 1.2 µV RMS). The electrodes were made from 99.9% Ag, were 10 mm long, 1 mm wide, with a distance of 10 mm between them. Each pre-amplifier was attached to a main amplifier unit that had a bandpass filter with cut-off frequencies at 20 ± 5 and 450 ± 50 Hz. This unit was connected to a PC via a Breakout Box (Median Electronic Industries Ltd., Dorset, UK) and a 16-bit analog-to-digital expansion board (PC516/DAQ, National Instruments, Austin, TX). The signal from each muscle was sampled at 1000 Hz using EMGworks (DelSys Inc., Boston, MA) acquisition software.

Electrodes were placed over the visual midpoint of the contracted belly of each of the four muscles of the dominant thigh with an angle of flexion of 45°. Electrodes were also aligned along a line approximately parallel to the direction of the underlying muscle fibres. The skin underlying the electrode sites was shaved and cleaned with soap and water prior to electrode placement. The electrodes were then coated with a thin film of conductive gel and, along with the pre-amplifier, attached to the skin using a double-sided adhesive interface. A single, circular ground electrode was attached to the patella.

The root mean square amplitude (RMS) of all raw EMGs (Fig. 1) was calculated over consecutive periods of 50 ms throughout the gait cycle, over the full range of motion for the isokinetic MVCs, and over the duration of each isometric MVC using Microsoft Excel.

3.5. Normalisation of gait EMGs

The isokinetic MVC method required EMGs recorded from both gait and isokinetic MVCs to be temporally related to the appropriate muscle kinematics. As SIMM/Gait calculated muscle lengths at 2% intervals of either the gait cycle or MVC range of motion, the EMGs also needed to be temporally normalised to this time base prior to amplitude normalisation by the four methods outlined below. This was accomplished by initially converting the duration of each gait cycle or MVC range of motion from seconds to percentages. A cubic spline was then fitted to the data to allow a new RMS EMG to be interpolated at each 2% interval of the gait cycle or range of motion.

The process of temporally normalising EMGs had the effect of further smoothing the RMS EMGs from both gait trials and isokinetic MVCs, as the original data consisted of more that 51 data points. The RMS EMGs recorded from the isometric MVCs were, therefore, also temporally normalised over the duration of the contraction in the same way. The peak EMG from the 2% intervals of the trial that produced the largest RMS EMG was then used as the denominator in the isometric MVC method. This was necessary to facilitate the subsequent comparison of the outputs from the isometric MVC method and the isokinetic MVC method. Gait EMGs were then normalised using the following four normalisation methods:

- Mean dynamic method: RMS EMGs from each gait cycle were expressed as a percentage of the mean RMS EMG calculated from all 2% intervals of the intra-individual ensemble average.
- Peak dynamic method: RMS EMGs from each gait cycle were expressed as a percentage of the peak RMS EMG from the 2% intervals of the intra-individual ensemble average.
- Isometric MVC method: RMS EMGs from each gait
cycle were expressed as a percentage of the peak RMS EMG from the isometric MVCs.

Isokinetic MVC method: RMS EMGs would ideally have been expressed as a percentage of peak RMS EMGs from the isokinetic MVCs with the identical muscle kinematics. However, it was discovered that muscle length could be in error by up to 10% as a consequence of inaccuracies in the process of mapping the musculoskeletal model to the participant. To account for this error, a range of ±10% of both muscle length and velocity were calculated throughout the gait cycle. Muscle kinematics from isokinetic MVCs were then matched with muscle kinematics that fell within this range, rather than with a specific muscle length and velocity. For example, an RMS EMG recorded during gait at a muscle length of 0.501 m and a shortening velocity of 0.179 m·s$^{-1}$ was normalised using the peak RMS EMG from an isokinetic MVC performed within the ranges of 0.451–0.551 m and 0.161–0.197 m·s$^{-1}$.

### 3.6. Assessment of intra-individual and inter-individual variability

The variance ratio (VR in Eq. (1)) devised by Hershler and Milner [18] was used to assess the intra-individual or stride-to-stride variability (i.e. reliability) of both the non-normalised and normalised gait EMGs for each muscle and for each individual.

$$\text{VR} = \frac{\sum_{i=1}^{k} \sum_{j=1}^{n} (X_{ij} - \bar{X}_i)^2 / k(n-1)}{\sum_{i=1}^{k} \sum_{j=1}^{n} (X_{ij} - \bar{X})^2 / (kn - 1)}$$

where, $k$ is the number of time intervals over the gait cycle (i.e. 51), $n$ is the number of trials (i.e. 3) for intra-individual variability, or the number of participants (i.e. 12) for inter-individual variability, $X_{ij}$ is the EMG value at the $i$th interval for the $j$th trial (intra-individual variability) or participant (inter-individual variability), and $\bar{X}_i$ is the mean of the EMG values at the $i$th time interval over $j$ gait cycles (intra-individual variability) or participants (inter-individual variability), $\bar{X}$ is the mean of the EMG values, i.e. $\bar{X} = \frac{1}{k} \sum_{i=1}^{k} \bar{X}_i$.

The variance ratio has previously been used to assess the variability of gait EMGs recorded from surface and fine-wire electrodes [19,20], left and right limbs [26], and from strides performed on different days [20] and at different speeds [30]. In addition, Gabel and Brand [16] demonstrated that this measure of variability is independent of the number of strides analysed, which is of particular importance considering that only three were used in this investigation. To enable comparisons with previous literature, the coefficient of variation (CV in Eq. (2)) was also used to assess intra-individual variability for each individual over the three strides.

$$\text{CV} = \frac{\sqrt{\frac{1}{k} \sum_{i=1}^{k} \sigma_i^2}}{\frac{1}{k} \sum_{i=1}^{k} |\bar{X}_i|}$$

where, $k$ is the number of time intervals over the gait cycle (i.e. 51), $\bar{X}_i$ is the mean of the EMG values at the $i$th interval calculated over three trials for intra-individual variability or 12 participants for inter-individual
variability, $\sigma_i$ is the standard deviation of the EMG values about $\bar{X}_i$, calculated over three trials for intra-individual variability or 12 participants for inter-individual variability.

Paired t-tests were used to compare the intra-individual variability of un-normalised gait EMGs with those normalised using the isokinetic MVC method. In contrast to the isokinetic MVC method, the isometric MVC, peak dynamic and mean dynamic methods used a single value as the denominator of their normalisation equation. As a consequence, the intra-individual variability of these latter three methods was identical to that of the un-normalised EMGs. Thus, it was only necessary to compare the intra-individual variability EMGs normalised by the isokinetic MVC method with that of the un-normalised EMGs.

Intra-individual or stride-to-stride ensemble averages were then created for each muscle and for each participant from the non-normalised EMGs and the output of each normalisation method. This was done by calculating the mean and standard deviation of the three strides at each 2% interval of the gait cycle. The variance ratio (Eq. (1)) and coefficient of variation (Eq. (2)) were again used to assess the variability of these mean EMG patterns, calculated from the intra-individual ensemble averages, across all participants (i.e. inter-individual variability).

Finally, to enable comparisons with previous literature, the intra-individual ensemble averages were further averaged across participants at each 2% interval to create an inter-individual ensemble average for the non-normalised EMGs and the output of each normalisation method from each muscle.

The isometric MVC method and the isokinetic MVC method both provided an output that was intended to represent the percentage of the maximal activation capacity of the muscles that occurred during normal walking. In order to compare the output of each method, the root mean square difference (RMSD in Eq. (3)) between the two normalisation methods was computed. To enable comparisons with previous literature, the absolute difference (ABSD in Eq. (4)) and the percentage difference ($\%D$ Eq. (5)) between the two methods were also calculated. A mean and SD was calculated for each of the three differences (Eqs. (3)–(5)) by including values from all gait cycles and for all participants.

$$\text{RMSD} = \sqrt{\frac{1}{k} \sum_{i=1}^{k} (X_{ia} - X_{ib})^2}$$

$$\text{ABSD} = \frac{1}{k} \sum_{i=1}^{k} |X_{ia} - X_{ib}|$$

$$\%D = \frac{1}{k} \sum_{i=1}^{k} \left( \frac{|X_{ia} - X_{ib}|}{X_{ib}} \right) \times 100$$

where, $k$ is the number of time intervals over the gait cycle (i.e. 51), $X_{ia}$ is the EMG value at the $i$th interval normalised using the isometric MVC method, and $X_{ib}$ is the EMG value at the $i$th interval normalised using the isokinetic MVC method.

4. Results

4.1. Amplitude and pattern of normalised gait EMGs

4.1.1. Intra-individual ensemble averages

Gait EMGs normalised by the isometric MVC method and isokinetic MVC method are shown, for one individual, in Figs. 2 and 3, respectively. The output of both of these methods revealed that gait EMGs were generally less than 20% of the amplitude recorded from MVCs. Some sections of the ensemble averages in Fig. 3 are missing as they could not all be normalised using the isokinetic MVC method. These gaps occurred because not all the maximum lengthening velocities experienced during gait were reached during the eccentric, isokinetic MVCs. More specifically, EMGs recorded during phases of the gait cycle that involved lengthening of the muscle in excess of approximately 0.1 m·s⁻¹ could not be matched with those recorded from eccentric, isokinetic MVCs performed at 2.62 rad·s⁻¹ or less.

As expected, the isometric MVC method, mean dynamic method and peak dynamic method all produced the same pattern of muscle activity for each muscle as that seen in the un-normalised gait EMGs. These three normalisation methods yielded the same pattern of gait EMGs as they all divided the un-normalised EMGs by a single reference value. However, Fig. 3 shows that the isokinetic MVC method yielded a slightly different pattern of gait EMGs than the other methods, as this method normalised gait EMGs from all three strides by using different reference values at each 2% interval of the gait cycle. Table 1 shows that, despite this, neither the root mean square difference nor absolute difference between the outputs of the isometric MVC and isokinetic MVC methods exceeded 3%. Thus, when compared using these techniques, the isometric MVC and isokinetic MVC methods yielded outputs that were very similar in both amplitude and pattern. The larger mean percentage difference (21–33%) between the two methods, shown in Table 1, occurred by virtue of the relatively small level of muscle activation that occurred during gait. As this formed the denominator of the equation used to calculate the percentage difference (Eq. (5)), it provided an inflated estimate of the difference between the two methods and was only used to enable comparison with previous research [24].
Fig. 2. Intra-individual ensemble average (± SD) of gait EMGs from the vastus lateralis (VL), vastus medialis (VM), biceps femoris (BF) and semitendinosus (ST) normalised using the *isometric MVC method*.

Fig. 3. Intra-individual ensemble average (± SD) of gait EMGs from the vastus lateralis (VL), vastus medialis (VM), biceps femoris (BF) and semitendinosus (ST) normalised using the *isokinetic MVC method*. The *isometric MVC method* ensemble average is also shown for comparison.
Table 1
Absolute, root mean square and percentage difference between the amplitude of gait EMGs normalised using the isometric MVC method and the isokinetic MVC method

<table>
<thead>
<tr>
<th></th>
<th>Semitendinosus</th>
<th>Biceps femoris</th>
<th>Vastus lateralis</th>
<th>Vastus medialis</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Absolute difference</strong></td>
<td>Mean</td>
<td>1.65</td>
<td>0.92</td>
<td>1.55</td>
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<td></td>
<td>SD</td>
<td>1.16</td>
<td>0.39</td>
<td>0.60</td>
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<td><strong>Root mean square</strong></td>
<td>Mean</td>
<td>2.36</td>
<td>1.49</td>
<td>2.17</td>
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<td></td>
<td>SD</td>
<td>1.47</td>
<td>0.51</td>
<td>0.74</td>
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<td><strong>Percentage difference</strong></td>
<td>Mean</td>
<td>24.6</td>
<td>20.8</td>
<td>32.9</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>10.9</td>
<td>6.28</td>
<td>12.0</td>
</tr>
</tbody>
</table>

4.1.2. Inter-individual ensemble averages

Un-normalised gait EMGs and those normalised by each method are shown in Figs. 4–8, respectively. In comparison to the intra-individual ensemble averages, the inter-individual ensemble averages shown in these figures displayed slightly different patterns of activity for each normalisation method. This occurred because regardless of the normalisation method that was used, each individual’s gait EMGs were normalised using a different reference value. As previously stated, the isokinetic MVC method was unable to normalise gait EMGs throughout the entire stride. This limitation is further demonstrated by the inter-individual ensemble average shown in Fig. 8, but not nearly to the same extent as the intra-individual ensemble average in Fig. 3. The inter-individual ensemble average (Fig. 8) displayed fewer gaps that the intra-individual curve because all the other participants had different muscle kinematics from the individual whose gait EMGs are represented in Fig. 3. To be more precise, other participants’ muscles reached a lengthening velocity that prevented their gait EMGs from being normalised by the isokinetic MVC method at different phases of the gait cycle. As such, different proportions of the other individuals’ gait cycle were normalised using the isokinetic MVC method. Thus, as the ensemble averages in Fig. 8 were amalgamated from all individuals, they collectively ensured that gait EMGs from almost all parts of the gait cycle were able to be normalised using the isokinetic MVC method.

4.2. Intra-individual variability of normalised gait EMGs

The intra-individual variability (i.e. reliability) of un-normalised EMGs from all the four muscles, averaged

![Fig. 4. Un-normalised root mean square (RMS) inter-individual ensemble average (± SD) of gait EMGs from the vastus lateralis (VL), vastus medialis (VM), biceps femoris (BF) and semitendinosus (ST).](image-url)
Fig. 5. Inter-individual ensemble average (± SD) of gait EMGs from the vastus lateralis (VL), vastus medialis (VM), biceps femoris (BF) and semitendinosus (ST) normalised using the mean dynamic method.

Fig. 6. Inter-individual ensemble average (± SD) of gait EMGs from the vastus lateralis (VL), vastus medialis (VM), biceps femoris (BF) and semitendinosus (ST) normalised using the peak dynamic method.

over individuals, is shown in Table 2. As previously stated, the intra-individual or stride-to-stride variability of EMGs following normalisation by the mean dynamic, peak dynamic, and isometric MVC normalisation methods (mean variance ratios = 0.23–0.26) was identical to that of the un-normalised EMGs, and so they are not included in Table 2. However, Table 2 shows that significantly greater ($P < 0.05$) intra-individual variability was seen in EMGs normalised by the isokinetic MVC method (mean variance ratios = 0.51–0.76).
Fig. 7. Inter-individual ensemble average (± SD) of gait EMGs from the vastus lateralis (VL), vastus medialis (VM), biceps femoris (BF) and semitendinosus (ST) normalised using the isometric MVC method.

Fig. 8. Inter-individual ensemble average (± SD) of gait EMGs from the vastus lateralis (VL), vastus medialis (VM), biceps femoris (BF) and semitendinosus (ST) normalised using the isokinetic MVC method. The isometric MVC method ensemble average is also shown for comparison.
Table 2
Intra-individual variability (VR = variance ratio; CV = coefficient of variation) of un-normalised gait EMGs* and gait EMGs normalised using the isokinetic MVC method

<table>
<thead>
<tr>
<th></th>
<th>Semitendinosus</th>
<th>Biceps femoris</th>
<th>Vastus lateralis</th>
<th>Vastus medialis</th>
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<tbody>
<tr>
<td>Un-normalised</td>
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</tr>
<tr>
<td>VR Mean</td>
<td>0.26</td>
<td>0.26</td>
<td>0.24</td>
<td>0.23</td>
</tr>
<tr>
<td>SD</td>
<td>0.13</td>
<td>0.10</td>
<td>0.15</td>
<td>0.12</td>
</tr>
<tr>
<td>CV Mean</td>
<td>0.41</td>
<td>0.50</td>
<td>0.46</td>
<td>0.47</td>
</tr>
<tr>
<td>SD</td>
<td>0.06</td>
<td>0.19</td>
<td>0.16</td>
<td>0.19</td>
</tr>
<tr>
<td>Isokinetic MVC</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VR Mean</td>
<td>0.51*</td>
<td>0.58*</td>
<td>0.76*</td>
<td>0.53*</td>
</tr>
<tr>
<td>SD</td>
<td>0.18</td>
<td>0.34</td>
<td>0.14</td>
<td>0.25</td>
</tr>
<tr>
<td>CV Mean</td>
<td>0.41</td>
<td>0.69</td>
<td>0.42</td>
<td>0.44</td>
</tr>
<tr>
<td>SD</td>
<td>0.08</td>
<td>0.24</td>
<td>0.14</td>
<td>0.15</td>
</tr>
</tbody>
</table>

* Intra-individual variance ratios and coefficients of variation were unaffected by the mean dynamic, peak dynamic and isometric MVC methods.

4.3. Inter-individual variability of normalised gait EMGs

The inter-individual variability of un-normalised and normalised EMGs from all four muscles is shown in Table 3. All normalisation methods generally reduced inter-individual variability in relation to un-normalised gait EMGs. The most homogeneous gait EMGs resulted from the mean dynamic method. Furthermore, the isometric MVC method reduced inter-individual variability slightly more than the isokinetic MVC method.

Table 3
Inter-individual variability (VR = variance ratio; CV = coefficient of variation) of un-normalised gait EMGs and gait EMGs normalised using the mean dynamic, peak dynamic, isometric MVC and isokinetic MVC methods

<table>
<thead>
<tr>
<th></th>
<th>Semitendinosus</th>
<th>Biceps femoris</th>
<th>Vastus lateralis</th>
<th>Vastus medialis</th>
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<tbody>
<tr>
<td>Un-normalised</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VR</td>
<td>1.00</td>
<td>0.73</td>
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<td>CV</td>
<td>2.04</td>
<td>0.86</td>
<td>1.38</td>
<td>1.11</td>
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<td>Mean dynamic</td>
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<tr>
<td>VR Mean</td>
<td>0.43</td>
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<td>0.30</td>
<td>0.27</td>
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<tr>
<td>CV Mean</td>
<td>0.48</td>
<td>0.57</td>
<td>0.48</td>
<td>0.48</td>
</tr>
<tr>
<td>Peak dynamic</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VR Mean</td>
<td>0.46</td>
<td>0.49</td>
<td>0.30</td>
<td>0.28</td>
</tr>
<tr>
<td>CV Mean</td>
<td>0.48</td>
<td>0.57</td>
<td>0.48</td>
<td>0.44</td>
</tr>
<tr>
<td>Isometric MVC</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>VR Mean</td>
<td>0.67</td>
<td>0.56</td>
<td>0.57</td>
<td>0.59</td>
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<tr>
<td>CV Mean</td>
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<td>0.71</td>
<td>0.74</td>
<td>0.75</td>
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<tr>
<td>Isokinetic MVC</td>
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<td></td>
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<td>VR Mean</td>
<td>0.74</td>
<td>0.59</td>
<td>0.88</td>
<td>0.89</td>
</tr>
<tr>
<td>CV Mean</td>
<td>0.77</td>
<td>0.55</td>
<td>0.72</td>
<td>0.82</td>
</tr>
</tbody>
</table>

methods only serve to inform the researcher or clinician about the level of activity displayed by a muscle throughout the gait cycle in relation to the average and maximum activity, respectively, recorded during gait. Alternatively, the isometric MVC and the isokinetic MVC methods are both designed to reveal how active a muscle is during gait in relation to its maximum static and dynamic activation capacity, respectively. These methods show that both vastii muscles were activated to approximately 15% of the value obtained from an MVC at the start of the gait cycle. These peak values are very similar to those reported for the same muscles during normal gait (e.g. [7,13,15]). In addition, both the biceps femoris and semitendinosus were activated to a similar level at the start and end of the gait cycle. This amplitude of activity again reflected that reported by the majority of previous research (e.g. [7,13,15]).

Minor differences in the level of muscle activation (mean = 1–2%) existed between the isometric MVC method and the isokinetic MVC method, when the difference was assessed using either the root mean square difference or absolute difference. The larger percentage difference (mean = 21–33%) between these methods was still generally lower than the 15–50% calculated by

5. Discussion

The overall aim of this investigation was to re-evaluate the three methods that have commonly been used to normalise EMGs recorded during normal gait, and to compare them with the isokinetic MVC method that has not previously been used in gait analysis. The outputs of both the mean dynamic and peak dynamic normalisation methods only serve to inform the researcher or clinician about the level of activity displayed by a muscle throughout the gait cycle in relation to the average and maximum activity, respectively, recorded during gait. Alternatively, the isometric MVC and the isokinetic MVC methods are both designed to reveal how active a muscle is during gait in relation to its maximum static and dynamic activation capacity, respectively. These methods show that both vastii muscles were activated to approximately 15% of the value obtained from an MVC at the start of the gait cycle. These peak values are very similar to those reported for the same muscles during normal gait (e.g. [7,13,15]). In addition, both the biceps femoris and semitendinosus were activated to a similar level at the start and end of the gait cycle. This amplitude of activity again reflected that reported by the majority of previous research (e.g. [7,13,15]).

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Mirka [24] between the isometric MVC method and a method similar to the isokinetic MVC method for the trunk muscles when working at a higher level of activation. The minor differences between the output of the isometric MVC method and the isokinetic MVC method support those previously discovered [5] for the biceps brachii, but do not agree with the significant differences reported previously [21] for the knee extensors and flexors.

The similarity in both the pattern and amplitude of gait EMGs normalised by the isometric MVC method and the isokinetic MVC method is a rational finding as the amplitude of EMGs recorded from isokinetic MVCs was similar to those recorded from isometric MVCs. Furthermore, EMGs from isokinetic MVCs were largely unaffected by the length of the musculotendinous unit or the rate at which it shortened or lengthened. However, as these relationships are not universally agreed upon (e.g. [3,6,17,32,37]), it is unsurprising that the findings of this investigation do not concur with the significant differences between the amplitude of the two methods that were reported by Kellis and Baltzopoulos [21]. Little explanation has been provided for the non-uniform relationships that have previously been reported between EMG and muscle action and EMG and muscle kinematics during MVCs, and a detailed discussion of them is beyond the scope of this article. However, the existence of such non-uniform relationships would result in much larger differences in the outputs of the isometric MVC method and the isokinetic MVC method than those shown in Figs. 3 and 8. How accurately the output of the isometric MVC method, or indeed the isokinetic MVC method, reflects the percentage of the maximal activation capacity required during gait cannot be answered by the findings of this investigation. However, a number of previous studies (e.g. [1]) have demonstrated that most individuals can maximally, or close to maximally, activate their muscles during isometric MVCs. These findings suggest that the isometric MVC method can yield EMGs that are an accurate representation of the degree of muscle activation that is required to walk.

The significantly greater ($P < 0.05$) intra-individual variability discovered for the isokinetic MVC method means that it results in less reliable EMGs than those that are un-normalised or normalised by the mean dynamic, peak dynamic or isometric MVC methods. As gait EMGs are often compared on different occasions or between different individuals, it should be desirable that any normalisation method yields EMGs that are at least as reliable as un-normalised EMGs. Thus, based on this criterion, the isokinetic MVC method should not be used in preference to other methods that are currently used.

The inter-individual variance ratios for the peak dynamic method shown in Table 3 compare very well with those presented by Pierotti et al. [30] for the same four muscles. However, the variance ratios for the same method calculated by Olree and Vaughan [26] are lower than those presented in Table 3. It has previously been noted that applying a greater degree of smoothing during the processing of gait EMGs, either by increasing the length of a moving average window [16,18,20] or reducing the cut off frequency of a linear envelope [36], reduces the intra-individual variability of gait EMGs. It is likely that this would also have the effect of reducing individual characteristics of gait EMGs and, as such, results in similar patterns between individuals. Thus, as Olree and Vaughan [26] processed their EMGs using a linear envelope with a cut off frequency of 3 Hz, it is possible that this was the cause of their low variability ratios. The inter-individual coefficients of variation presented in Table 3 are very similar to previously reported values [38,39,41] for both un-normalised EMGs and those normalised by the mean dynamic method. Unlike the variance ratio, the coefficient of variation is essentially the ratio between the standard deviation and the mean. Both these measures would be similarly affected by the degree of smoothing that occurred during processing, resulting in little if any effect on the overall coefficient of variation. Thus, despite their EMGs being processed using a linear envelope with a cut off frequency of 3 Hz, previously reported inter-individual coefficients of variation [38,39,41] are comparable to those in Table 3.

In agreement with Yang and Winter [41], the mean dynamic and peak dynamic normalisation methods reduced inter-individual variability of gait EMGs most in relation to the un-normalised EMGs. These findings are demonstrated in Table 3 by both lower variance ratios and coefficients of variation. Despite apparent agreement between these two measures of variability, the coefficient of variation should be treated with caution when it is used to compare the variability of different measures (i.e. the outputs of different normalisation methods). This is because the mean value of the measurement forms the denominator of the equation used to calculate the coefficient of variation and, therefore, has the potential to either elevate or reduce the coefficient. The variance ratios in Table 3 also show that, in agreement with Shiavi et al. [34,35], normalisation by the mean dynamic method resulted in a slightly more homogeneous pattern of gait EMGs than the peak dynamic method. This is understandable as the peak activity that occurs during gait may be quite high for some individuals, in relation to the activity in the remainder of the stride, but not for others. The mean EMG would conceal such variability in peak EMG and, as such, reduce inter-individual variability when used as the normalisation factor.

Both the isometric MVC and isokinetic MVC methods also resulted in similar, lower inter-individual variance ratios than the un-normalised EMGs for most of the muscles analysed. However, as with the sub-MVC
method used by Yang and Winter [41], these MVC methods did not create as homogeneous a pattern of gait EMGs as either the mean or peak dynamic methods. This is likely because EMGs from MVCs have previously been shown to be more unreliable than those from sub-maximal contractions (e.g. [40]), and because some individuals are able to activate their muscles closer to the maximum level of activation than others (e.g. [1]). Both these factors will likely contribute to minor differences in the amplitude of the output of the isometric and isokinetic MVC methods and increase the inter-individual variability over the mean and peak dynamic methods. Previous authors [2,23] warned against using normalisation methods that reduce the true variation of EMG patterns between individuals. Despite this, the findings of this study support previous research (e.g. [2,40]) that all normalisation methods increase the homogeneity of EMGs from different individuals in relation to the un-normalised EMGs to some greater or lesser extent.

6. Conclusion

The isokinetic MVC method resulted in EMGs that had greater intra-individual variability, and were therefore less reliable, than un-normalised EMGs or those normalised by the mean dynamic, peak dynamic or isometric MVC methods. The findings of this investigation also agree with previous research [23,34,35,41] that the dynamic methods, and in particular the mean dynamic method, yield the most homogeneous templates of muscle activity during gait. This is noteworthy as the variance ratio was used to assess inter-individual variability, which does not suffer from the same limitations as the coefficient of variation that was used in earlier studies. Thus, being one of the main focuses of gait research in recent years, if the aim is to solely produce a normal EMG template for comparison against, for example, that from pathological gait, then clearly the mean dynamic method should be used.

However, the mean and peak dynamic methods have two limitations that have previously been recognised. First, as a consequence of reducing inter-individual variability, they remove the true variation that exists in a normal group of gait EMGs. Secondly, due to the nature of the normalisation factor in both the mean and peak dynamic methods, they do not inform the researcher or clinician of the degree of muscle activation that is required during gait. The only methods that have the potential to provide such information, as a consequence of the nature of their normalisation factors, are the isometric MVC and isokinetic MVC methods. This investigation found that there is little difference in the amplitude and pattern of the output of these two normalisation methods. Based on these findings, it would be futile to spend additional time and effort using the isokinetic MVC method in preference to the isometric MVC method. However, before the isokinetic MVC method can finally be discounted, the confusion surrounding the relationship between the amplitude of EMGs and both the type muscle contraction and the muscle kinematics during MVCs needs to be clarified.

Acknowledgements

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References


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